Comparison of top-quark-pair cross section measurements with NNLO+NNLL predictions

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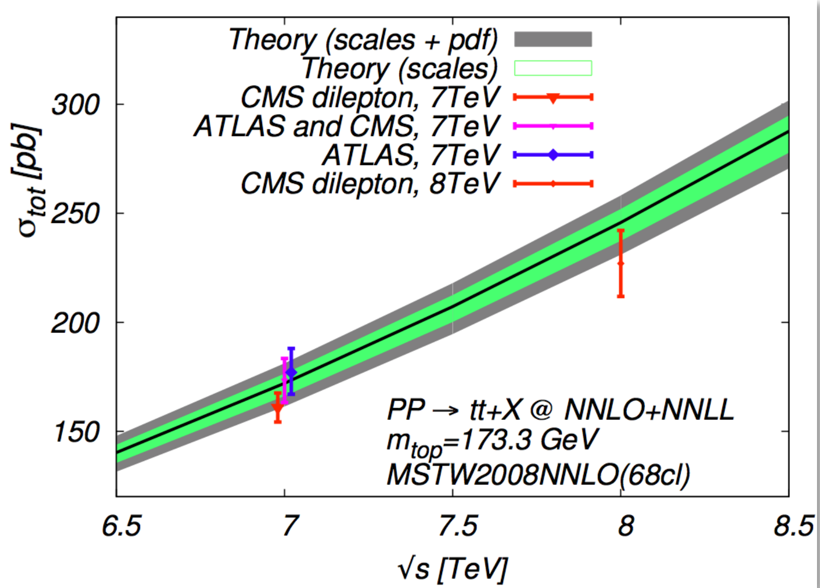
PHYSICS AT THE TERA SCALE
Helmholtz Alliance

Outline

- Introduction
- Software tools
- Uncertainties
  - Scale
  - PDF and α_S
- Mass and $\sqrt{s}$ dependence

Introduction

- Theoretical calculation for $t\bar{t}$ production available up to NNLO+NNLL (also for gg → $t\bar{t}$):



Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	+0.110(1.5%) −0.200(2.8%)	+0.169(2.4%) −0.122(1.7%)
LHC 7 TeV	172.0	+4.4(2.6%) −5.8(3.4%)	+4.7(2.7%) −4.8(2.8%)
LHC 8 TeV	245.8	+6.2(2.5%) −8.4(3.4%)	+6.2(2.5%) −6.4(2.6%)
LHC 14 TeV	953.6	+22.7(2.4%) −33.9(3.6%)	+16.2(1.7%) −17.8(1.9%)

Very precise: 2.2% (Tevatron), ~ 3% (LHC)

[Czakon, Fiedler, Mitov, arXiv:1303.6254]

- Public programs available to perform these calculations for specific parameter choice:
  - HATHOR (v1.5) → exact NNLO $t\bar{t}$ cross section **[Aliev et al., arXiv:1007.1327]**
  - Top++ (v2.0) → exact NNLO and NNLO+NNLL resummed $t\bar{t}$ cross section **[Czakon, Mitov, arXiv:1112.5765]**

- In this talk we present reference cross sections at NNLO+NNLL for different parameter choices and propose a common ATLAS-CMS reference recommendation
  - **scale, PDF and α_S, top-quark mass, centre-of-mass energy ($\sqrt{s}$)**

Software tools

- Results in this talk are presented using the Top++ (v2.0) program:
  - NNLO with soft gluon resummation at NNLL
  - m_{top} = 172.5 GeV ; some results also given at m_{top}(Tevatron) = 173.20 ± 0.87 GeV
  - scale: $\mu_R = \mu_F = m_{top}$

- The choice of the m_{top} value is only **temporary** (world-average m_{top} is foreseen):
  - Simulations are performed assuming m_{top} = 172.5 GeV
  - Experimental parametrisation for the mass dependence of $\sigma(t\bar{t})$ is not (yet) available for all measurements
  - Once available, the measured $\sigma(t\bar{t})$ can be corrected to the world-average m_{top} and compared to the corresponding prediction

Cross-checks at exact NNLO using HATHOR (v1.5) yielded differences at the sub per-mille level

→ Many thanks to **Dennis Wendland** (ATLAS, Humboldt University Berlin) for the studies !

Scale uncertainty

- **Proposal**: consider *restricted scale variation* (used also by Czakon et al.): vary μ_R , μ_F independently by a factor of 2 while never allowing them to differ by more than a factor of 2 from each other
  - Scale uncertainty defined by taking the envelope of the resulting cross section values
  - Example: MSTW2008NNLO PDF at 7 TeV (m_{top} = 172.5 GeV)

	$\mu_R(m_t)$	$\mu_F(m_t)$	σ (pb)
	0.5	0.5	177.233
	0.5	1	172.372
	1	0.5	177.921
Central value	1	1	176.228
	1	2	170.241
	2	1	180.791
	2	2	178.747

Largest variations: ~3.5%

  - Similar results obtained with CT10 NNLO or NNPDF2.3 NNLO PDF sets

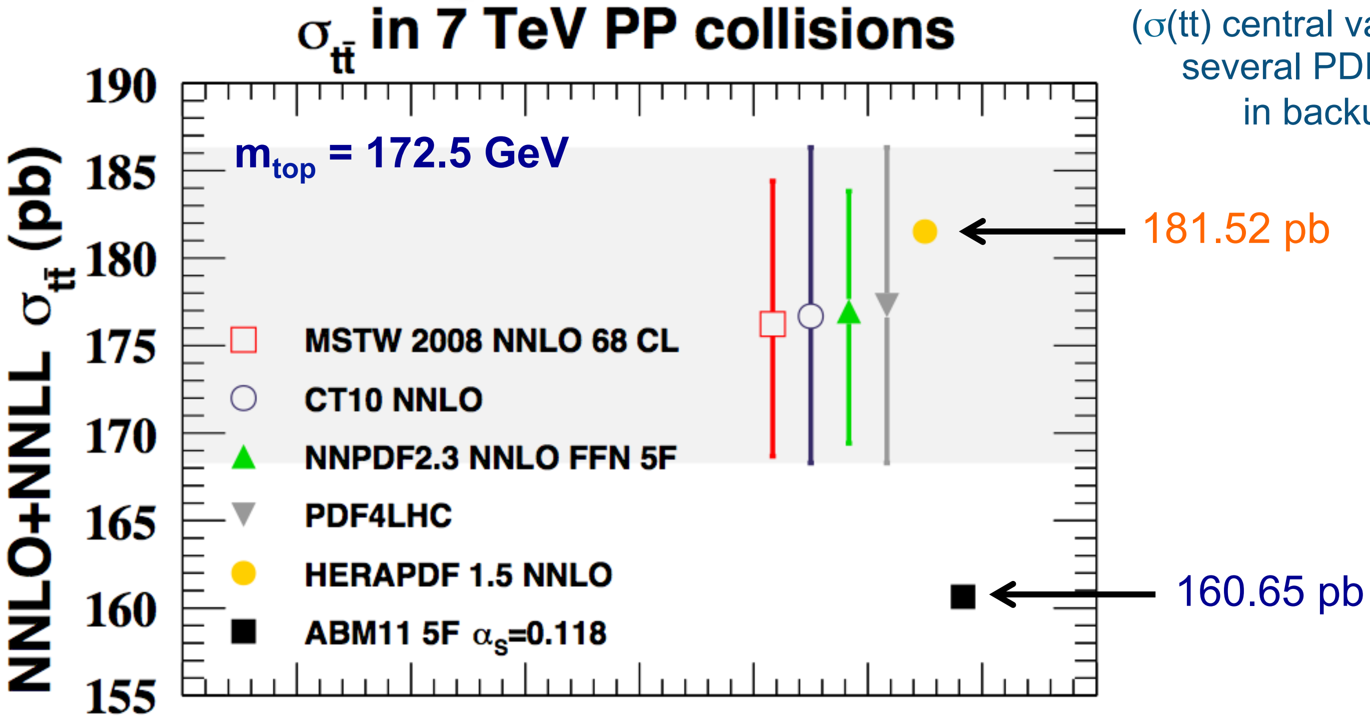
PDF and α_S uncertainty

- **Proposal**: PDF4LHC-style treatment for joint PDF+α_S uncertainty:
  - Evaluate 68% CL PDF uncertainties at most similar available α_S
    - CT10 NNLO(*), NNPDF2.3 NNLO with $\alpha_S = 0.118$
    - MSTW2008 NNLO at fitted value $\alpha_S = 0.117$
  - Evaluate 68% CL α_S uncertainty
    - MSTW2008 use MSTW prescription for 68% CL PDF+α_S
    - CT10 NNLO and NNPDF2.3 NNLO evaluate variation for ±0.002 (90% CL), reduce to 68% CL, and add in quadrature to 68% PDF uncertainty (**)
  - Use envelope of PDF+α_S uncertainties
- Illustrated for $\sqrt{s}$ = 7, 8, 13, 14 GeV in the following slides

(*) Scale down by factor 1.645 for 90% to 68%

(**) Not following NNPDF group recommendation for α_S here

PDF and α_s uncertainty: 7 TeV

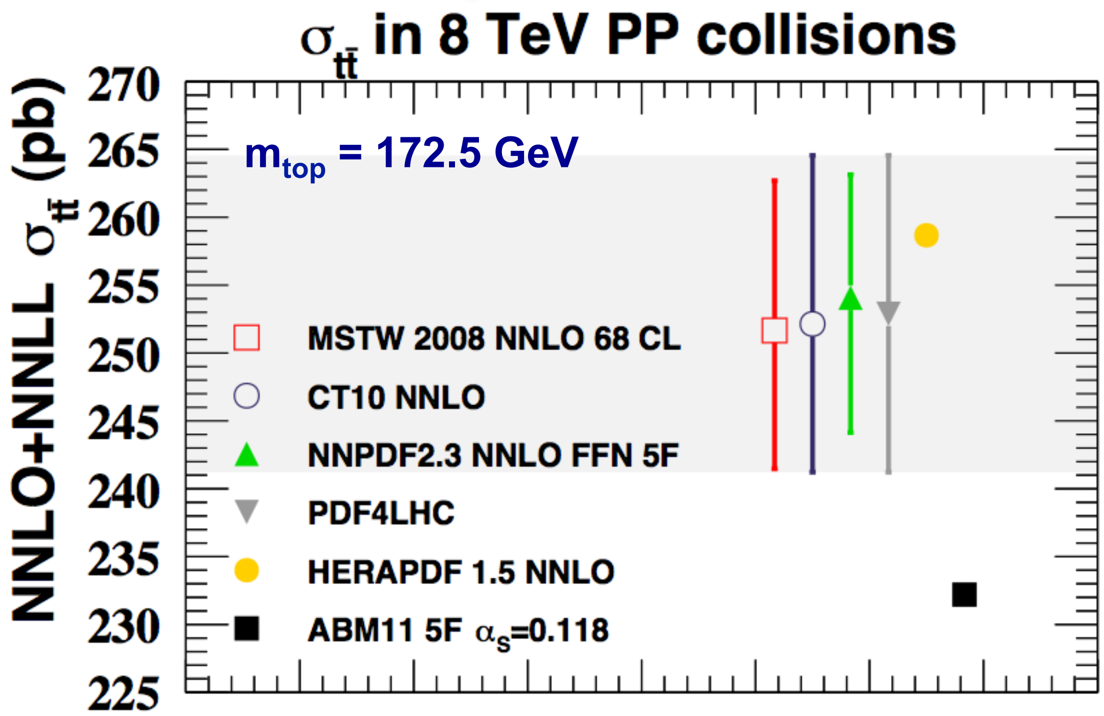


(σ(tt) central values for several PDF sets in backup)

PDF set	$\alpha_S(M_Z)$	σ (pb), $\sqrt{s} = 7$ TeV
MSTW2008NNLO 68%	0.117±0.0014	$176.23^{+8.17}_{-7.55}$
CT10 NNLO (@68%)	0.118 ±0.0012	$176.68^{+9.64}_{-8.39}$
NNPDF2.3 NNLO (5f FFN)	0.118 ±0.0012	$176.96^{+6.86}_{-7.54}$
PDF4LHC (inc. α_S)	—	$177.3^{+9.02}_{-9.02}$

- Good agreement between different PDF sets (largest difference: ~10% ABM11)
- Dominated by CT10 PDF set uncertainties

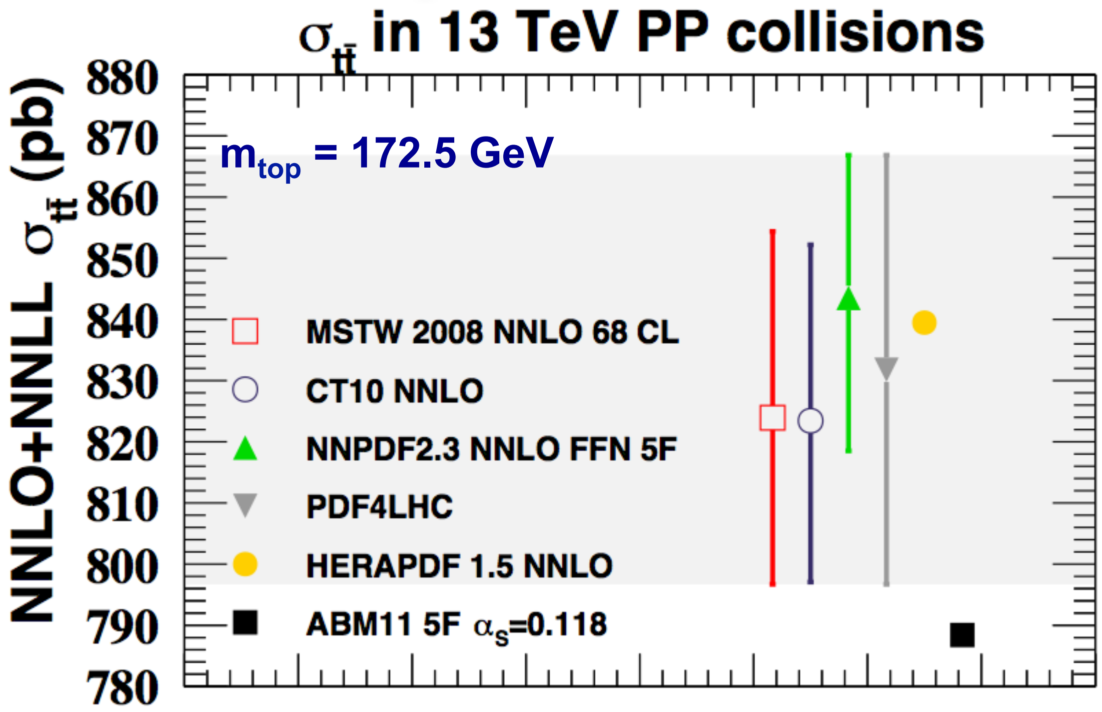
PDF and α_S uncertainty: 8 TeV



PDF set	$\alpha_S(M_Z)$	σ (pb), $\sqrt{s} = 8$ TeV
MSTW2008NNLO 68%	0.117±0.0014	$251.66^{+11.04}_{-10.19}$
CT10 NNLO (@68%)	0.118 ±0.0012	$252.14^{+12.42}_{-10.92}$
NNPDF2.3 NNLO (5f FFN)	0.118 ±0.0012	$254.07^{+9.07}_{-9.93}$
PDF4LHC (inc. α_S)	—	$252.89^{+11.67}_{-11.67}$

- Good agreement between different PDF sets (largest difference: ~10% ABM11)
- Dominated by CT10 PDF set uncertainties

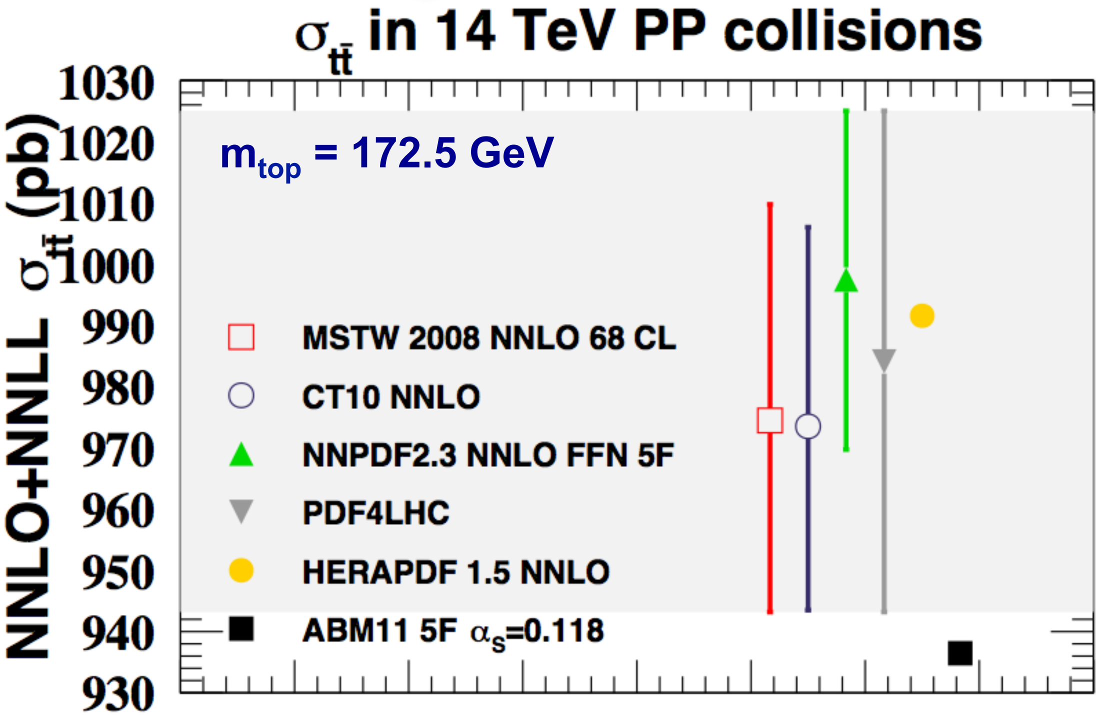
PDF and α_s uncertainty: 13 TeV



PDF set	$\alpha_S(M_Z)$	σ (pb), $\sqrt{s} = 13$ TeV
MSTW2008NNLO 68%	0.117±0.0014	$823.93^{+30.46}_{-27.23}$
CT10 NNLO (@68%)	0.118 ±0.0012	$823.43^{+28.77}_{-26.37}$
NNPDF2.3 NNLO (5f FFN)	0.118 ±0.0012	$843.51^{+23.34}_{-25.00}$
PDF4LHC (inc. α_S)	—	$831.77^{+35.08}_{-35.08}$

- Good agreement between different PDF sets (largest difference: ~10% ABM11)
- Some divergence between NNPDF, CT10, MSTW2008 start to appear

PDF and α_S uncertainty: 14 TeV



PDF set	$\alpha_S(M_Z)$	σ (pb), $\sqrt{s} = 14$ TeV
MSTW2008NNLO 68%	0.117±0.0014	$974.46^{+35.29}_{-31.27}$
CT10 NNLO (@68%)	0.118 ±0.0012	$973.51^{+32.51}_{-30.02}$
NNPDF2.3 NNLO (5f FFN)	0.118 ±0.0012	$997.47^{+27.55}_{-27.75}$
PDF4LHC (inc. α_S)	—	$984.11^{+40.92}_{-40.92}$

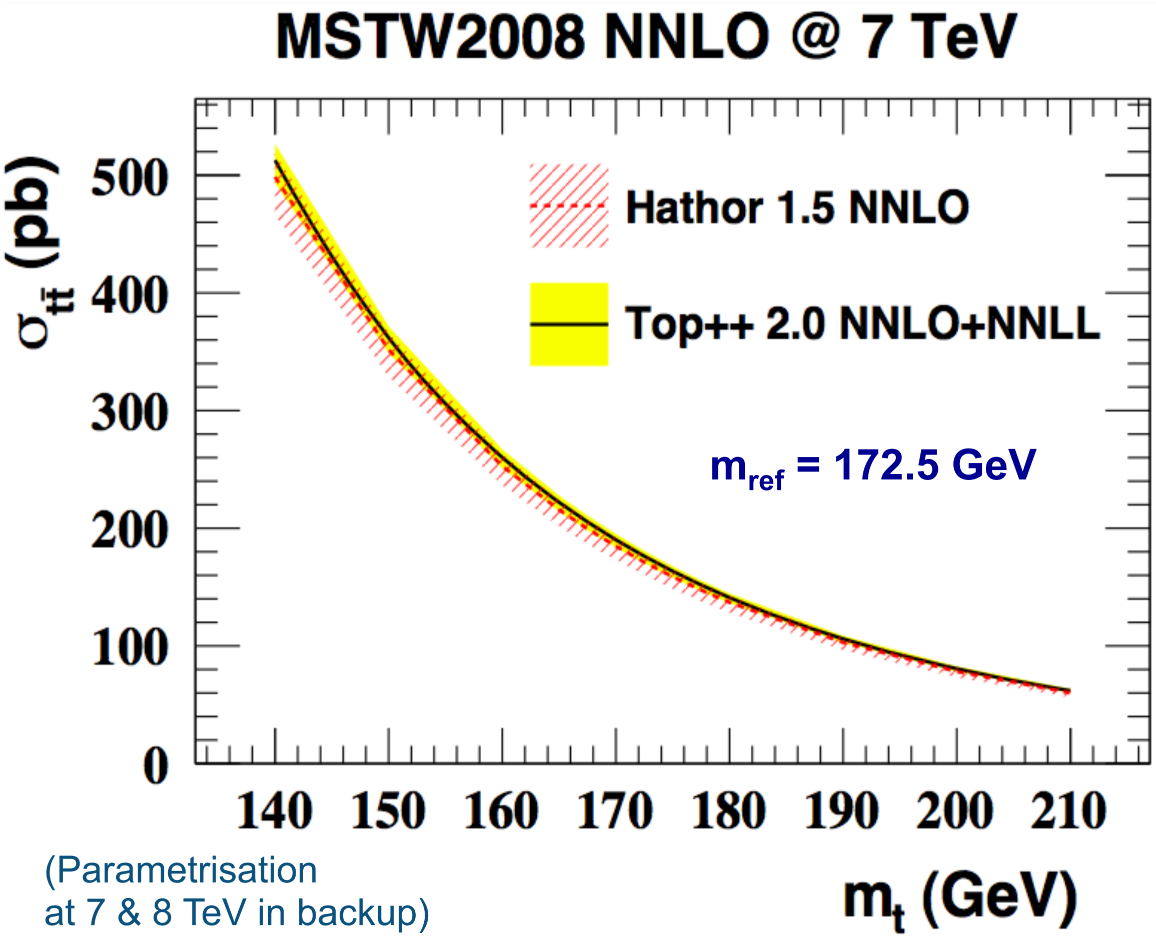
- Good agreement between different PDF sets (largest difference: ~10% ABM11)
- Some divergence between NNPDF, CT10, MSTW2008 start to appear

Mass dependence of $\sigma(t\bar{t})$

- The $t\bar{t}$ cross section has a strong dependence on m_{top}

$$\sigma(m_t) = \sigma(m_{\rm ref}) \left(\frac{m_{\rm ref}}{m_t}\right)^4 \left[1 + a_1 \left(\frac{m_t - m_{\rm ref}}{m_{\rm ref}}\right) + a_2 \left(\frac{m_t - m_{\rm ref}}{m_{\rm ref}}\right)^2\right]$$

[Czakon, Fiedler, Mitov, arXiv:1303.6254]



(Parametrisation at 7 & 8 TeV in backup)

- Compare NNLO vs. NNLO+NNLL: Good agreement within scale uncertainties (bands)
- Proposed m_{top} variation to quote cross section uncert:

± 1.0 GeV

→ gives, for the cross section:

+5.44 pb / - 5.26 pb	(for m_{top} = 172.5 GeV)
+5.32 pb / - 5.14 pb	(for m_{top} = 173.2 GeV)

Current combinations:

m_{top}(Tevatron) = 173.20 ± 0.87 GeV

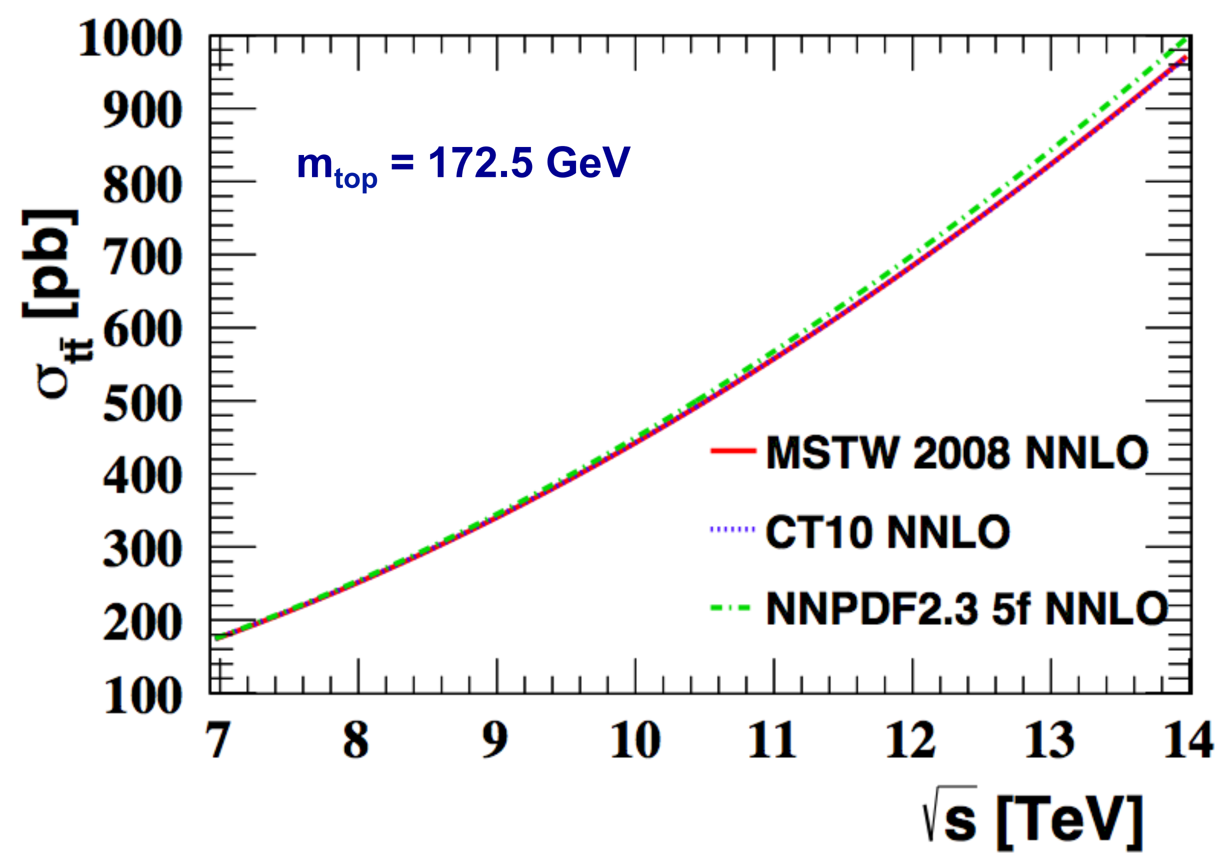
m_{top}(LHC) = 173.29 ± 0.95 GeV

Dependence of $\sigma(t\bar{t})$ on $\sqrt{s}$

- Parametrisation of the dependence on $\sqrt{s}$:

[Langenfeld et al., arXiv:0907.2527]

$$\sigma_{t\bar{t}} = a_0 + \sqrt{s}\left[a_1 + a_3 \ln\left(\frac{\sqrt{s}}{14\,\text{TeV}}\right) + a_4 \ln^2\left(\frac{\sqrt{s}}{14\,\text{TeV}}\right)\right] + s\left[a_2 + a_5 \ln\left(\frac{\sqrt{s}}{14\,\text{TeV}}\right) + a_6 \ln^2\left(\frac{\sqrt{s}}{14\,\text{TeV}}\right)\right]$$



- Compare central PDF sets for MSTW2008, CT10, NNPDF:
  - Good agreement for MSTW and CT10 over the full range
  - NNPDF gives higher values at large $\sqrt{s}$

(See backup for results at 7 and 8 TeV, also for m_{top} = 173.2 GeV)

Results

- **Proposal**: recommendation for most analyses:
  - **Total uncertainty = scale ± PDF+α_S, added in quadrature**
  - For search analyses, m_{top} can be added in quadrature as well

Recommended σ($t\bar{t}$) at m_{top} = 172.5 GeV

7 TeV	$177.31^{+4.56}_{-5.99}$ (scale) $^{+5.44}_{-5.26}$ (m_t) $^{+9.02}_{-9.02}$ (PDF+α_S) pb.
8 TeV	$252.89^{+6.39}_{-8.64}$ (scale) $^{+7.58}_{-7.33}$ (m_t) $^{+11.67}_{-11.67}$ (PDF+α_S) pb.
13 TeV	$831.77^{+19.77}_{-29.20}$ (scale) $^{+32.26}_{-30.83}$ (m_t) $^{+35.08}_{-35.08}$ (PDF+α_S) pb.
14 TeV	$984.11^{+23.22}_{-34.68}$ (scale) $^{+37.74}_{-36.09}$ (m_t) $^{+40.92}_{-40.92}$ (PDF+α_S) pb.

Recommended σ($t\bar{t}$) at m_{top} = 173.2 GeV

7 TeV	$173.60^{+4.46}_{-5.85}$ (scale) $^{+5.32}_{-5.14}$ (m_t) $^{+8.85}_{-8.85}$ (PDF+α_S) pb
8 TeV	$247.74^{+6.26}_{-8.45}$ (scale) $^{+7.41}_{-7.16}$ (m_t) $^{+11.47}_{-11.47}$ (PDF+α_S) pb.

Comparisons

- Compare 8 TeV value to reference from Czakon, Mangano, Mitov, Rojo arXiv:1303.7215(*):

Reference (m_{top} = 173.3 GeV)	Central (pb)	Scale	PDF+α_S	m_{top}	Total
CMMR (CT10)	246.3	+6.4 - 8.6	+11.2 - 9.6	+7.4 - 7.1	+19.8 (+8.1%) - 20.5 (-8.3%)
This method	247.0	+6.3 - 8.5	+11.4 - 11.4	+7.4 - 7.1	+15.0 (+6.0%) - 15.9 (-6.4%)

  - CMMR: smaller central value, since not using PDF4LHC prescription
  - CMMR: smaller PDF uncertainty, since not using PDF4LHC prescription
  - CMMR: smaller α_S variation ± 0.0007
  - CMMR: PDF+α_S and m_{top} added in quadrature, then linearly to scale (more conservative)

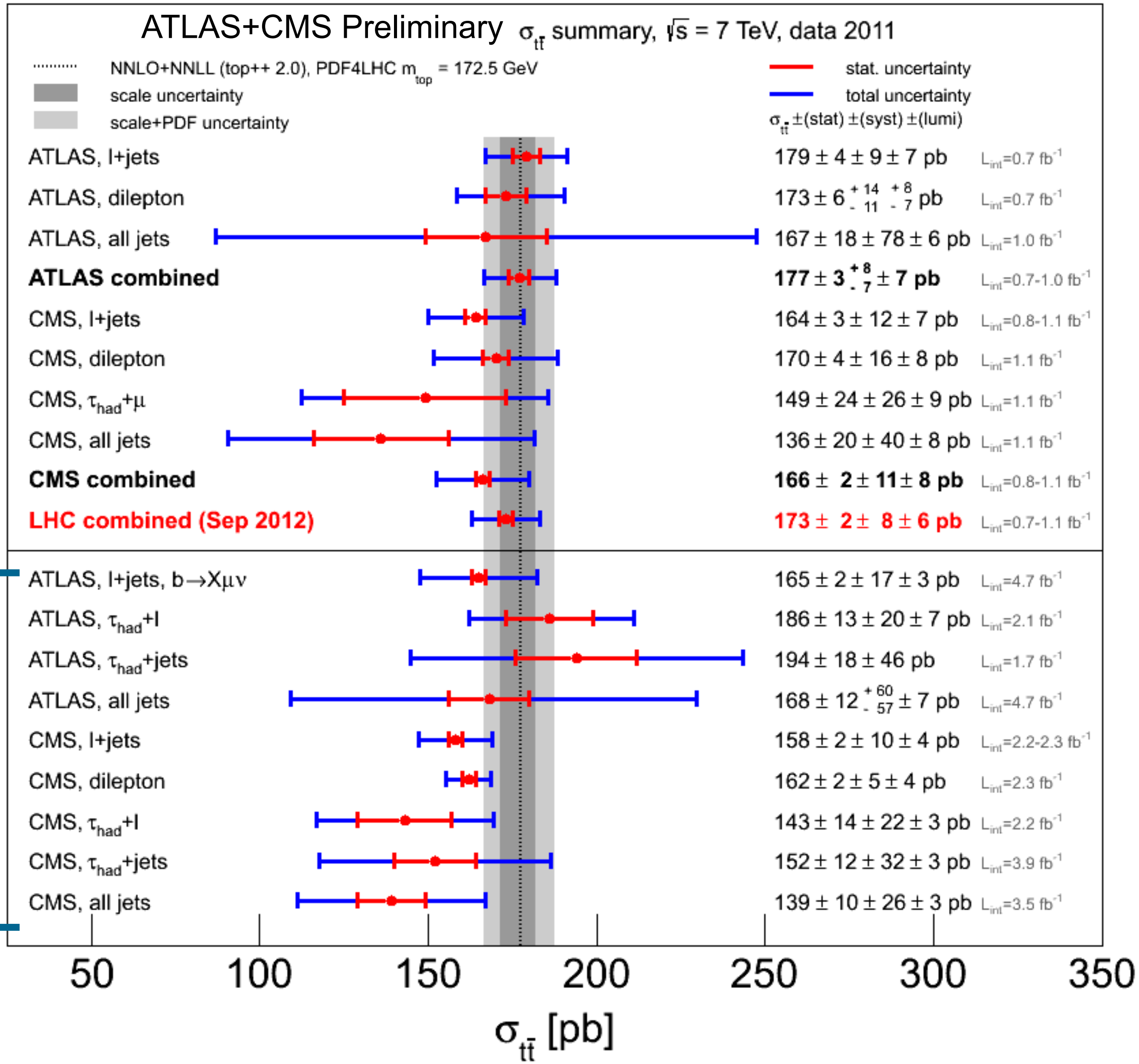
- Individual uncertainties in this method are more conservative than in CMMR, but the combination is more aggressive

(*) Constraints on the gluon PDF from top quark pair production at hadron colliders

Summary of LHC $\sigma(t\bar{t})$ results @ 7 TeV

Using
m_{top} = 172.5 GeV
as a temporary fix until experiments provide parametrisation for the mass dependence

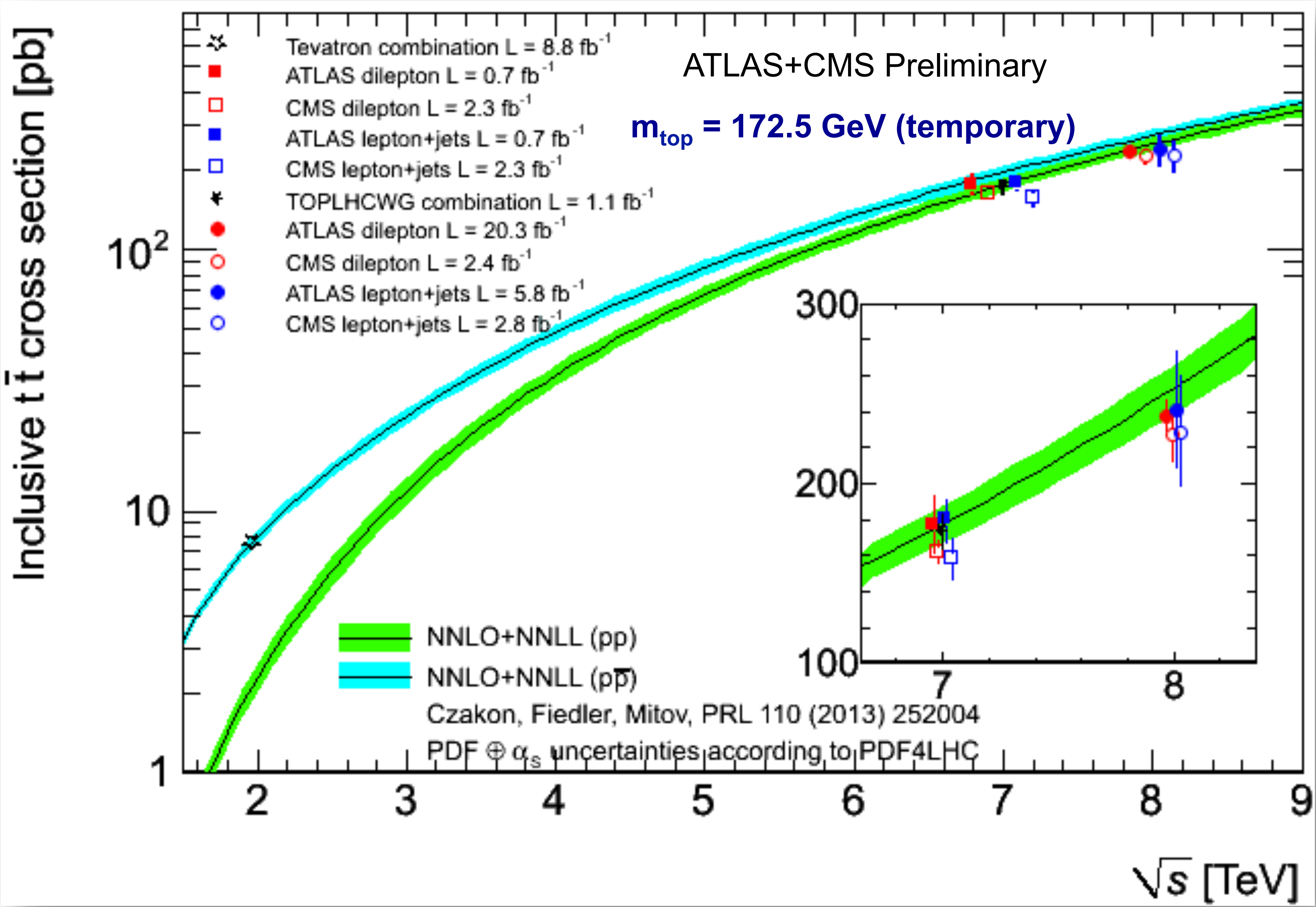
New or updated measurements, not included in current LHC combination



Plan for future combinations:

- Provide LHC combination at 7 TeV with updated results
- Combine 8 TeV results as soon as updated CMS measurement is released

$\sigma(t\bar{t})$ as a function of $\sqrt{s}$



Summary

- Predictions for $\sigma(t\bar{t})$ have been prepared using Top++ in a common ATLAS-CMS effort
  - Results from running Top++(v2.0) were cross-checked by both ATLAS & CMS, obtaining identical results in all cases where direct comparison was made

- Central values with NNLO PDFs and their associated uncertainties have been calculated

- A combined reference value, using a PDF4LHC procedure for PDF and α_S uncertainties, restricted scale variation and providing an associated m_{top} uncertainty is now ready for use at 7 and 8 TeV

- Parametrisations vs. m_{top} allow this result to be quoted at any (reasonable) top mass

- We propose that these results be used to provide a common reference cross section for $t\bar{t}$ production to be used by ATLAS & CMS collaborations

- The results will be documented on a TOPLHCWG twiki, including information to ensure correct referencing of the theoretical work

Additional information

NNLO+NNLL $\sigma(t\bar{t})$ for different PDFs – 7 TeV

Central NNLO+NNLL cross section values for different PDF sets:

PDF set	$\alpha_S(M_Z)$	σ (pb), $\sqrt{s} = 7\,\text{TeV}$
ABM11 [17]	0.1134	139.23
ABM12 [18]	0.1132	140.571
ATLAS-epWZ12 [19]	0.1176	171.52
CT10 NNLO	0.118	176.68
HERA1.5 NNLO [20]	0.1176	181.52
JR09 VFN [21]	0.112	175.05
MSTW2008 NNLO	0.117	176.23
MSTW2008 CPdeut NNLO [22]	0.117	174.66
NNPDF2.3 NNLO (5f FFN)	0.118	176.96

[17] S. Alekhin, J. Blumlein, and S. Moch, Phys.Rev. **D86** (2012) 054009, arXiv:1202.2281 [hep-ph].

[18] S. Alekhin, J. Bluemlein, and S. Moch, arXiv:1310.3059 [hep-ph].

[19] ATLAS Collaboration Collaboration, G. Aad et al., Phys.Rev.Lett. **109** (2012) 012001, arXiv:1203.4051 [hep-ex].

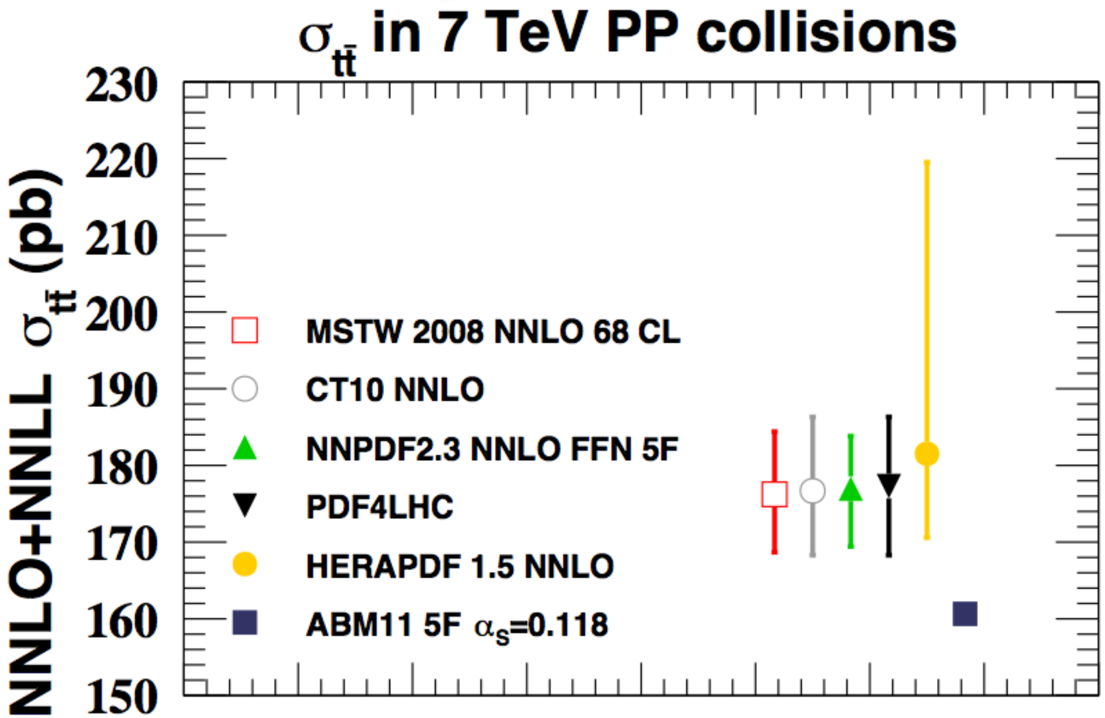
[20] ZEUS Collaboration, H1 Collaboration Collaboration, A. Cooper-Sarkar, PoS **EPS-HEP2011** (2011) 320, arXiv:1112.2107 [hep-ph].

[21] P. Jimenez-Delgado and E. Reya, Phys.Rev. **D79** (2009) 074023, arXiv:0810.4274 [hep-ph].

P. Jimenez-Delgado and E. Reya, Phys.Rev. **D80** (2009) 114011, arXiv:0909.1711 [hep-ph].

[22] A. Martin, A. T. Mathijssen, W. Stirling, R. Thorne, B. Watt, et al., Eur.Phys.J. **C73** (2013) 2318, arXiv:1211.1215 [hep-ph].

PDF and α_s uncertainty: 7 TeV

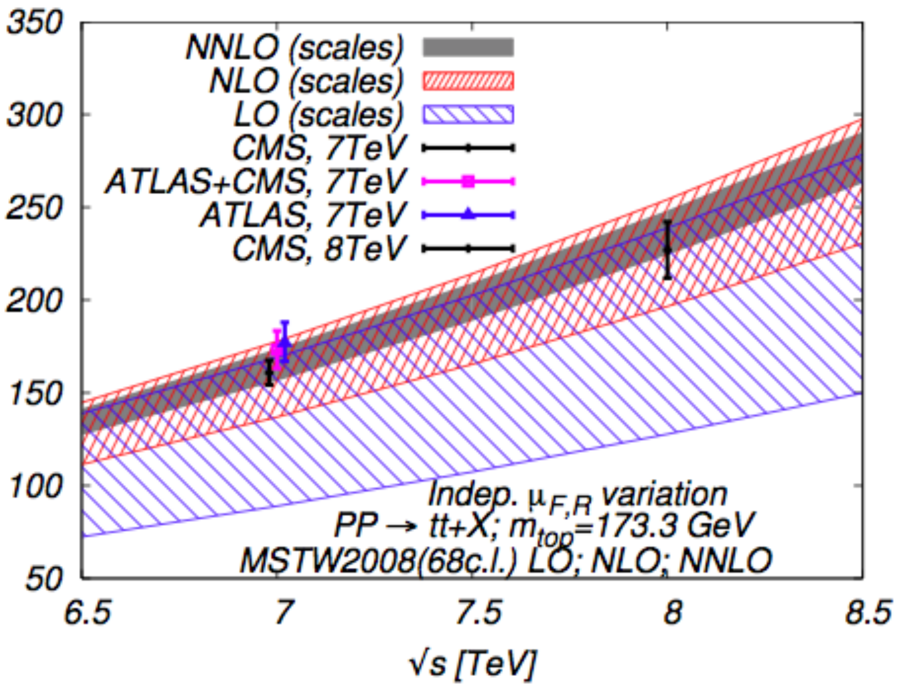


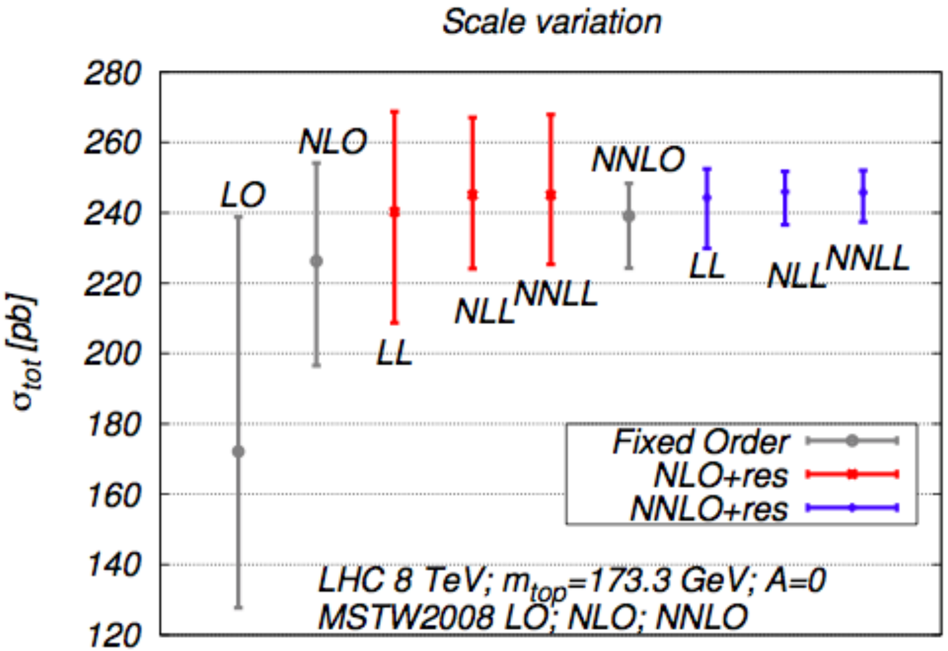
PDF set	$\alpha_S(M_Z)$	σ (pb), $\sqrt{s} = 7$ TeV
MSTW2008NNLO 68%	0.117±0.0014	$176.23^{+8.17}_{-7.55}$
CT10 NNLO (@68%)	0.118 ±0.0012	$176.68^{+9.64}_{-8.39}$
NNPDF2.3 NNLO (5f FFN)	0.118 ±0.0012	$176.96^{+6.86}_{-7.54}$
PDF4LHC (inc. α_S)	—	$177.3^{+9.02}_{-9.02}$

- Good agreement between different PDF sets (largest difference: ~10% ABM11)
- Dominated by CT10 PDF set uncertainties

Scale dependence at different orders

- Reference: Czakon et al., arXiv:1305.3892





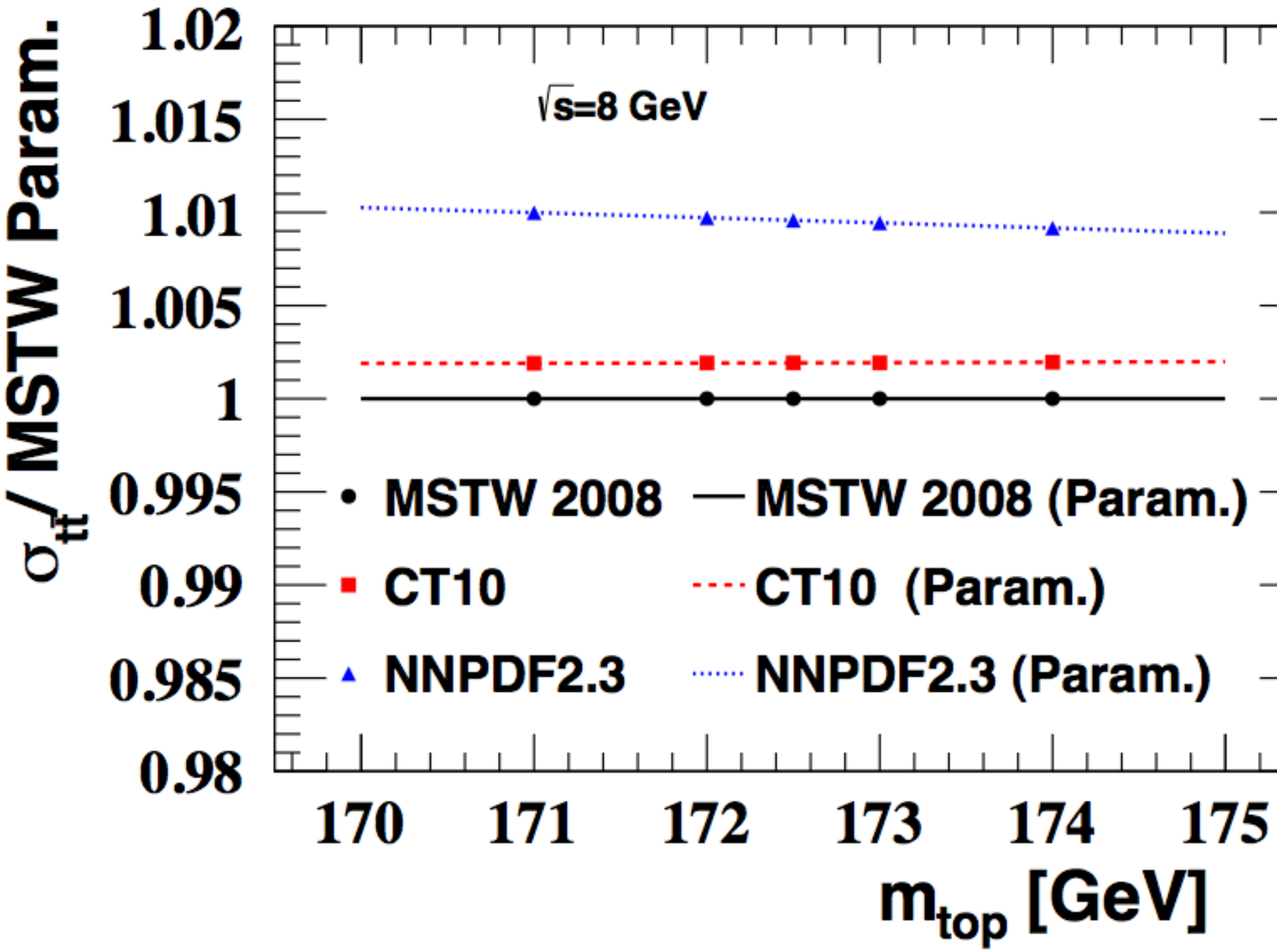
Mass dependence (m_{ref} = 172.5 GeV) – 7 TeV

PDF set	m_{ref} (GeV)	$\sigma(m_{ref})$ (pb)	a_1	a_2
MSTW2008NNLO 68% (Upper PDF)	172.5	184.399	-1.20104	0.861453
MSTW2008NNLO 68% (Upper Scale)	172.5	180.791	-1.22023	0.856356
MSTW2008NNLO 68% (Central)	172.5	176.227	-1.21489	0.874646
MSTW2008NNLO 68% (Lower Scale)	172.5	170.241	-1.19952	0.827074
MSTW2008NNLO 68% (Lower PDF)	172.5	168.295	-1.24635	0.323325
CT10 NNLO (@68%) (Upper PDF)	172.5	186.312	-1.17041	0.877029
CT10 NNLO (@68%) (Central)	172.5	176.680	-1.21135	0.751272
CT10 NNLO (@68%) (Lower PDF)	172.5	168.295	-1.24635	0.323325
NNPDF2.3 NNLO (5f FFN) (Upper PDF)	172.5	182.215	-1.24172	0.855243
NNPDF2.3 NNLO (5f FFN) (Central)	172.5	176.956	-1.26738	0.891085
NNPDF2.3 NNLO (5f FFN) (Lower PDF)	172.5	171.697	-1.29460	0.929122

Mass dependence (m_{ref} = 172.5 GeV) – 8 TeV

PDF set	m_{ref} (GeV)	$\sigma(m_{ref})$ (pb)	a_1	a_2
MSTW2008NNLO 68% (Upper PDF)	172.5	262.696	-1.08108	0.706000
MSTW2008NNLO 68% (Upper Scale)	172.5	258.051	-1.09749	0.716215
MSTW2008NNLO 68% (Central)	172.5	252.143	-1.08952	0.809901
MSTW2008NNLO 68% (Lower Scale)	172.5	243.020	-1.07738	0.654935
MSTW2008NNLO 68% (Lower PDF)	172.5	241.468	-1.10559	0.732067
CT10 NNLO (@68%) (Upper PDF)	172.5	264.575	-1.05535	0.341195
CT10 NNLO (@68%) (Central)	172.5	252.143	-1.08952	0.809901
CT10 NNLO (@68%) (Lower PDF)	172.5	241.226	-1.11977	0.797665
NNPDF2.3 NNLO (5f FFN) (Upper PDF)	172.5	260.790	-1.11666	0.700475
NNPDF2.3 NNLO (5f FFN) (Central)	172.5	254.069	-1.13972	0.727908
NNPDF2.3 NNLO (5f FFN) (Lower PDF)	172.5	247.348	-1.16404	0.756831

Mass dependence (m_{ref} = 172.5 GeV) – 8 TeV



$\sqrt{s}$ dependence (m_{ref} = 172.5 GeV)

Variation	a_0	a_1	a_2	a_3	a_4	a_5	a_6
MSTW2008NNLO 68%							
+ PDF	-18.80	0.00398389	4.95967×10^{-6}	-0.00482021	0.00193168	1.62628×10^{-6}	-1.79909×10^{-6}
+ Scale	-19.76	0.00392783	4.91380×10^{-6}	-0.00454488	0.00213225	1.64519×10^{-6}	-1.74334×10^{-6}
Central	-19.28	0.00407370	4.78034×10^{-6}	-0.00491610	0.00193429	1.65770×10^{-6}	-1.75344×10^{-6}
− Scale	-18.69	0.00372065	4.62761×10^{-6}	-0.00429468	0.00201460	1.55236×10^{-6}	-1.64551×10^{-6}
− PDF	-19.45	0.00402450	4.62610×10^{-6}	-0.00490523	0.00192739	1.68838×10^{-6}	-1.68330×10^{-6}
CT10 NNLO (@68%)							
+ PDF	-17.39	0.00362820	4.96189×10^{-6}	-0.00443341	0.00185404	1.50363×10^{-6}	-1.76287×10^{-6}
Central	-19.30	0.00410105	4.77232×10^{-6}	-0.00495292	0.00194119	1.62089×10^{-6}	-1.78803×10^{-6}
− PDF	-20.81	0.00457705	4.59383×10^{-6}	-0.00535759	0.00199018	1.72091×10^{-6}	-1.79453×10^{-6}
NNPDF2.3 NNLO (5f FFN)							
+ PDF	-44.30	-0.0256241	7.29534×10^{-6}	-0.00434345	0.00762476	-5.72878×10^{-7}	-6.80907×10^{-7}
Central	-45.75	-0.0256303	7.16572×10^{-6}	-0.00458430	0.00774642	-5.50412×10^{-7}	-6.72349×10^{-7}
− PDF	-46.54	-0.0253236	7.00456×10^{-6}	-0.00474690	0.00776910	-4.78635×10^{-7}	-6.46907×10^{-7}

$\sqrt{s}$ dependence (m_{ref} = 173.2 GeV)

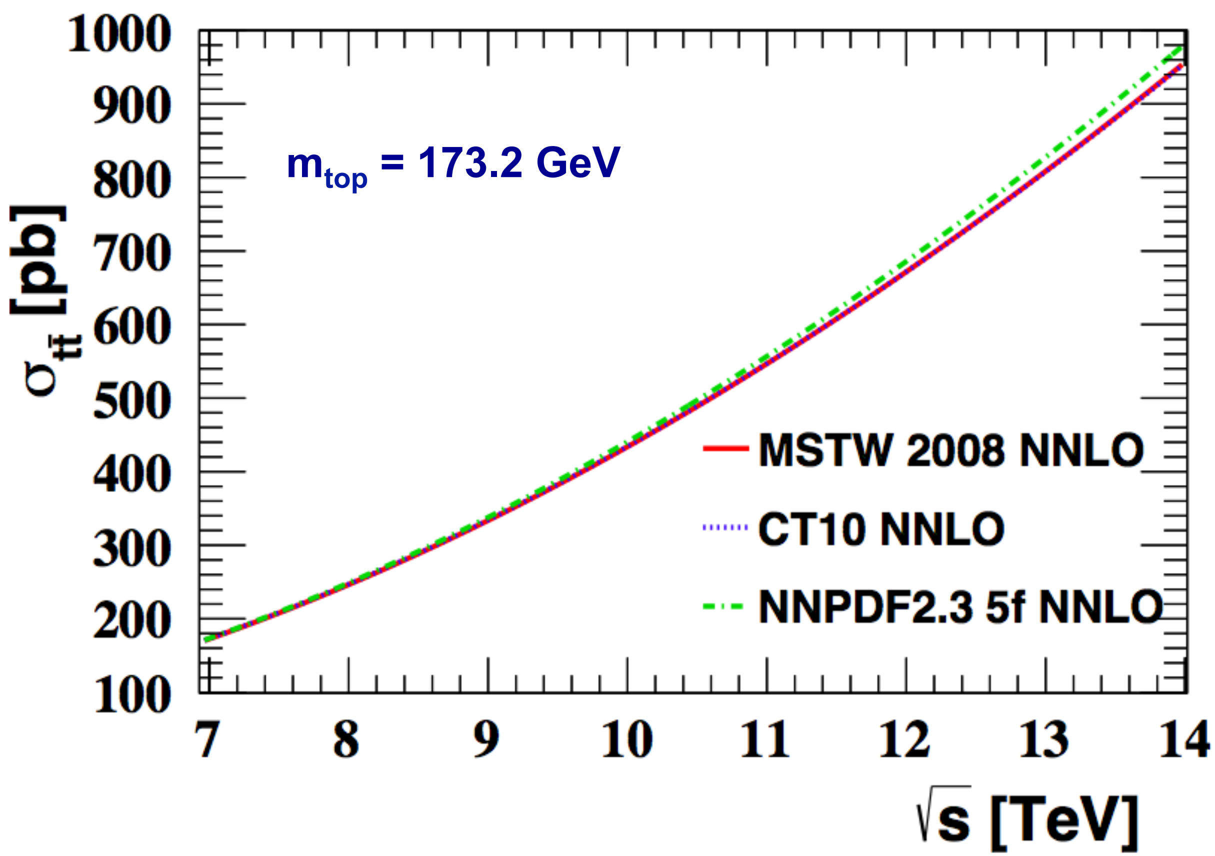
Variation	a_0	a_1	a_2	a_3	a_4	a_5	a_6
MSTW2008NNLO 68%							
+ PDF	-18.57	0.00385085	4.87119×10^{-6}	-0.00473736	0.00191442	1.60497×10^{-6}	-1.75922×10^{-6}
+ Scale	-19.59	0.00371280	4.83381×10^{-6}	-0.00443529	0.00213516	1.61919×10^{-6}	-1.69621×10^{-6}
Central	-19.07	0.00392072	4.69773×10^{-6}	-0.00482777	0.00192138	1.63695×10^{-6}	-1.71155×10^{-6}
− Scale	-18.52	0.00351355	4.55303×10^{-6}	-0.00418933	0.00201730	1.52798×10^{-6}	-1.60045×10^{-6}
− PDF	-19.22	0.00386881	4.54640×10^{-6}	-0.00481344	0.00191358	1.66656×10^{-6}	-1.64183×10^{-6}
CT10 NNLO (@68%)							
+ PDF	-17.22	0.00353537	4.87221×10^{-6}	-0.00439071	0.00183139	1.48953×10^{-6}	-1.72819×10^{-6}
Central	-19.06	0.00402416	4.68395×10^{-6}	-0.00490402	0.00190975	1.60719×10^{-6}	-1.75313×10^{-6}
− PDF	-20.55	0.00451036	4.50708×10^{-6}	-0.00528626	0.00196010	1.70551×10^{-6}	-1.75876×10^{-6}
NNPDF2.3 NNLO (5f FFN)							
+ PDF	-43.43	-0.0251342	7.15922×10^{-6}	-0.00424718	0.00747672	-5.39449×10^{-7}	-6.55703×10^{-7}
Central	-44.61	-0.0250416	7.02474×10^{-6}	-0.00445204	0.00756176	-5.04876×10^{-7}	-6.42961×10^{-7}
− PDF	-45.55	-0.0248067	6.87071×10^{-6}	-0.00463549	0.00760642	-4.44076×10^{-7}	-6.21333×10^{-7}

Dependence of σ(tt̄) on √s

- Parametrisation of the dependence on √s:

[Langenfeld et al., arXiv:0907.2527]

$$\sigma_{t\bar{t}} = a_0 + \sqrt{s}\left[a_1 + a_3 \ln\left(\frac{\sqrt{s}}{14\,\mathrm{TeV}}\right) + a_4 \ln^2\left(\frac{\sqrt{s}}{14\,\mathrm{TeV}}\right)\right] + s\left[a_2 + a_5 \ln\left(\frac{\sqrt{s}}{14\,\mathrm{TeV}}\right) + a_6 \ln^2\left(\frac{\sqrt{s}}{14\,\mathrm{TeV}}\right)\right]$$



- Compare central PDF sets for MSTW2008, CT10, NNPDF:
  - Good agreement for MSTW and CT10 over the full range
  - NNPDF gives higher values at large √s

Dependence of σ(tt̄) on √s